Spin Physics Results at PHENIX

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We report the longitudinal and transverse spin physics results of the PHENIX experiment. The first goal of the longitudinal spin physics program is to measure the contribution of the gluon spin to the proton spin. We have measured double helicity asymmetries (A_{LL}) of neutral pion at midrapidity and other signal channels. In the transverse spin physics program, we have measured the transverse single spin asymmetries (A_N) of pions at midrapidity, neutrons at forward rapidity, and so on. Prospects from the current and future runs at PHENIX will be discussed.

1 Introduction

1.1 Spin Puzzle

Since the EMC experiment at CERN [1] showed that the quark spin carries only a small portion of the nucleon spin 1/2, it has been one of the biggest issues in the high-energy hadron physics to know what is the origin of the nucleon spin. The nucleon spin is described by:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g.$$

Contributions other than that from the quark spin ($\Delta\Sigma$) come from the gluon spin (ΔG) and the orbital angular momenta of quarks and gluons ($L_q + L_g$).

In order to investigate the contribution of the gluon spin with high sensitivity, experiments at CERN and DESY have been performing semi-inclusive asymmetry measurements of the deep-inelastic polarized lepton scattering off the polarized nucleon targets.[2, 3] We are performing asymmetry measurements of the polarized proton-proton collisions at RHIC in BNL.

In this article, double helicity asymmetry (A_{LL}) results by the longitudinally-polarized proton collisions with the PHENIX detector will be reported and discussed for the measurements of the gluon-spin contribution so far at RHIC.

We will also report the measurements of the transverse single-spin asymmetries (SSA), or A_N, by the transversely-polarized proton collisions at PHENIX, and discuss the results and the relation to the contribution of the orbital angular momenta of the quarks and gluons to the nucleon spin.

1.2 Polarized Proton Collisions at RHIC

RHIC is a unique collider for the QCD physics operated as a relativistic heavy-ion collider to study a new state of matter, so-called quark-gluon plasma [4], and as a polarized-proton collider for the high-energy spin physics.

As the polarized-proton collider, there are many special magnets to keep and manipulate polarization, so-called snake magnets and spin rotators, and polarimeters to measure the polarization installed in the facility. Collisions with a luminosity of 3×10^{31} cm^{-2} s^{-1} is achieved at $\sqrt{s} = 200$ GeV, and in the future 6×10^{31} cm^{-2} s^{-1} in 200 GeV collisions and 1.5×10^{32} cm^{-2} s^{-1} in 500 GeV collisions will be achieved. Polarization of 65% polarization is achieved and 70% will be achieved in the future.

1.3 PHENIX Experiment

Philosophies of the PHENIX detector design are high resolution at the cost of acceptance, high rate capable DAQ, and excellent trigger capability for rare events.[5] We have two central arms and two muon arms in the forward and backward directions. Other important detectors are global detectors. We have beam-beam counters (BBC) and zero-degree calorimeters (ZDC).

The 2006 run finished in June. We had several mode of proton physics runs and test runs in this year. First we took 200 GeV radial-spin run and accumulated a luminosity (L) of 2.7 pb^{-1} with 57% polarization (P) Secondly we took 200 GeV longitudinal-spin run and accumulated $L = 7.5$ pb^{-1} with 62% polarization. We accumulated a figure-of-merit (FoM $= LP^2$) of 0.88 pb^{-1} in the radial-spin run, and FoM ($= LP^4$) of 1.11 pb^{-1} for the longitudinal spin run. After these runs, we had a short 22 GeV test, and had 62.4 GeV transverse and longitudinal physics runs for two weeks. At the end, we had a 500 GeV machine study. In this year, the 200 GeV radial-spin run accumulated about 20-times larger luminosity and more than 200-times larger FoM compared with the 2002 transverse-spin run. The 200 GeV longitudinal-spin run accumulated twice larger luminosity and 5-times larger FoM even compared with the last-year run. Recorded data volumes were around 300 TB each year in these two years. This was achieved by the progress of the DAQ system, which has 5 kHz DAQ rate now. Another big achievement we had is a WAN data transfer from BNL to RIKEN in Japan with 60 MB/s sustained rate. This enables us immediate data reconstruction and production with large CPU power of CCJ, computing center in Japan.

2 A_{LL} Results

2.1 ΔG Measurements

In polarized proton collisions, ΔG is extracted from A_{LL} measurements:

$$A_{LL} = \frac{d\sigma_{++} - d\sigma{+-}}{d\sigma_{++} + d\sigma{+-}} = \frac{1}{P_1 P_2} \cdot \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}},$$

which is composed by measurements of polarization (P), yield of the signal channel (N), and relative luminosity ($R = L_{+-}/L_{++}$).

The relative luminosity is measured and evaluated with two global detectors, BBC and ZDC. BBC covers pseudo-rapidity region from 3 to 3.9, and have very low background and high statistics. ZDC covers pseudo-rapidity region more than 6, very different kinematics and acceptance region from those of BBC. Bunch-by-bunch comparison is performed for ratio of scalar counts of BBC and ZDC, which is fitted by the expected polarization pattern, with a constant and A_{LL} of BBC relative to ZDC as fitting parameters after vertex-width correction in each bunch collision. Fill-by-fill fitting result shows constant zero-consistent value of A_{LL} of BBC relative to ZDC which shows a precision of the relative luminosity and indicates no A_{LL} of both BBC and ZDC. In 2005, we achieved precision smaller than 10^{-4} and it corresponds to the relative luminosity contribution to A_{LL} measurements of signal channels smaller than 0.023% with 47% beam polarization.

Next important measurement is a longitudinal component measurement at PHENIX with a local polarimeter. A large asymmetry of forward neutron production was discovered in the IP12 measurement at RHIC for the development of the local polarimeter used in the PHENIX experiment.[6] By using a electromagnetic calorimeter and a hadron calorimeter located in the most-forward region, about 18 m away from the interaction point, a large, about -10%, A_N of neutron was measured in the kinematic region, $x_F > 0.2$ and $p_T < 0.3$ GeV/c, while asymmetries of photons and neutral pions were zero consistent. At PHENIX, the neutron asymmetry at the forward rapidity has been measured by ZDC, hadron calorimeters located about 18 m away from the interaction point, with shower-maximum detectors (SMD) which consist of plastic scintillator arrays in the vertical and horizontal directions.

Spin rotator magnets enable longitudinal collisions at PHENIX. When the rotators are off, the azimuthal angle distribution of the forward neutron shows the asymmetry pattern, but once the rotators are turned on, the asymmetry shows very small asymmetry. Longitudinal component is evaluated from the smallness of this asymmetry. The 2005 run showed the longitudinal components are $99.48 \pm 0.12 \pm 0.02$% in one beam (Blue beam), and $98.94 \pm 0.21 \pm 0.04$% in another (Yellow beam).

2.2 Results and Discussions

Based on these measurements, we have measured A_{LL} of neutral pions. Neutral pions are produced from various types of parton reactions. We know gluon-gluon and quark-gluon processes are dominant in relatively low p_T region, so that the π^0 measurement is sensitive to the gluon reaction. Before the A_{LL} measurement, we confirmed that the π^0 cross section shows excellent agreement with next-to-leading order (NLO) perturbative QCD (pQCD) calculations.[7]

Left panel of Fig.1 shows A_{LL} of π^0 measured in 2005 run with four theoretical curves based on NLO pQCD.[9, 10] Owing to huge statistics of pions and the high-energy photon trigger, A_{LL} of π^0 can be measured with a good accuracy. Moreover, the progress in the accelerator performance made the precision of A_{LL} improved significantly from previous years.[8] The result disfavors a large ΔG and excludes scenarios where $\Delta G = G$ (GRSV-max) and $\Delta G = -G$ are used at the input energy scale of $Q^2 = 0.4$ GeV^2. GRSV-std represents the case of the best fits to the DIS data.

We have also measured A_{LL} of multi-particles. In this measurement, charged

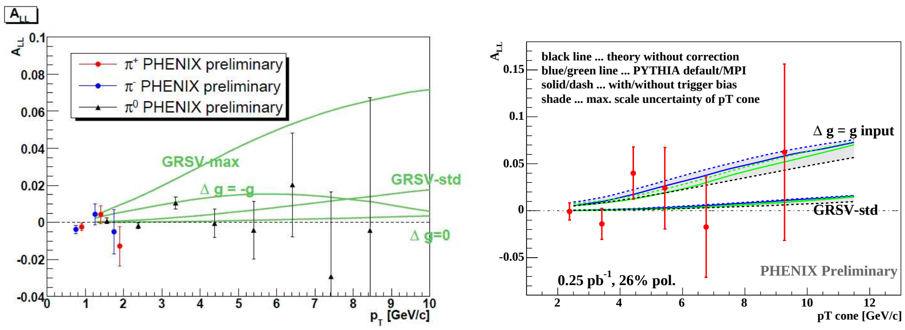

Fig. 1. Left: A_{LL} of neutral and charged pions measured in 2005 run with NLO pQCD curves. A_{LL} of charged pions are useful to estimate the contamination from the soft QCD process. Right: A_{LL} of multi-particles measured in 2003 run with theory curves.

particles are detected by tracking detectors and photons are detected by electromagnetic calorimeters. This measurement is expected to cover higher Bjorken x region of the ΔG measurement. Right panel of Fig.1 shows A_{LL} of multi-particles measured in the 2003 run with theoretical curves. $p_{T\text{cone}}$ is a sum of p_T of detected charged particles and photons within a cone of $\sqrt{\eta^2 + \phi^2} = 0.3$. The ratio of the $p_{T\text{cone}}$ to the real p_T of initial parton is estimated to be about 80% and the theory p_T scale was normalized by a PYTHIA simulation. Variation of theory curves represents systematic uncertainties of the p_T scale and indicates that the measurement have a sensitivity to restrict ΔG in the future with a high enough statistics.[11]

2.3 Outlook

In 2006, we took $\sqrt{s} = 62.4$ GeV data to measure the A_{LL} of the neutral pion.[12] It will give us a high-x coverage of the A_{LL} measurement in addition to the measurements at $\sqrt{s} = 200$ GeV, although we need to investigate the cross section of the neutral pion and know the applicability of the pQCD in this energy region.

We also newly installed the muon-piston calorimeter (MPC) in 2006. It consists of PWO crystals located behind the BBC, and cover the forward rapidity region, $3.1 < |\eta| < 3.65$. The A_{LL} measurement of neutral pion production by the MPC will give us a coverage of another different kinematic region.

After we accumulate much enough statistics until 2009 at $\sqrt{s} = 200$ GeV, we will get a result of A_{LL} measurement of direct photon production, as shown in the right panel of Fig.2. We have already measured a cross section of direct photon production to show the excellent applicability of the pQCD, as shown in the left panel of Fig.2.[13]

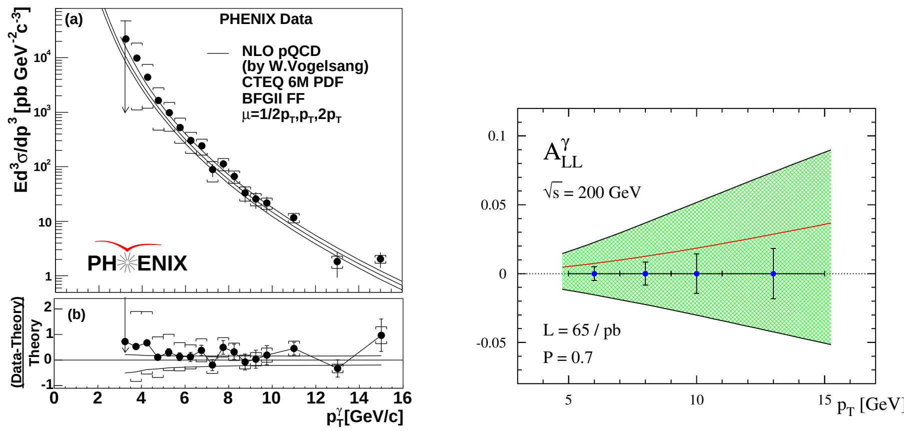

Fig. 2. Measured cross section of direct photon production compared with a pQCD calculation (left) and projection of the A_{LL} measurement after we accumulated statistics until 2009 (right).

3 A_N Results

3.1 Single-Spin Asymmetries

Experiments to measure the gluon-spin contribution to the nucleon spin have shown initial results and indicated possible small contribution. Importance of the transverse-spin experiments are increasing, because many transverse-spin phenomena can be regarded as consequences of the transverse motion in the nucleon, so that their relation to the contribution of the orbital angular momenta to the nucleon spin.

In the polarized hadron scattering experiments, significant transverse single-spin asymmetries (A_N) of neutral and charged pion production were measured at the forward rapidity in the Fermilab E704 experiment, a fixed-target experiment at $\sqrt{s} = 19.4$ GeV.[14] A similar asymmetry of neutral pion production has been measured at the forward rapidity in the RHIC/STAR experiment with a collider energy, $\sqrt{s} = 200$ GeV.[15]

In order to explain these results, many QCD-based theories have bee developed. One is so-called Collins effect which explains the results with a combination of the transversity distribution function, $\delta q(x) = h_{1T}(x)$ and the Collins fragmentation function, $H_1^\perp(z, k_T^2)$.[16] The transversity distribution is a distribution of the transverse-spin of a parton inside the transversely polarized proton, and the Collins fragmentation function is a correlation between the transverse spin of a fragmenting quark and the transverse momentum of the outgoing hadron relative to the quark (k_T^2). Another is so-called Sivers effect which explains the results with the Sivers

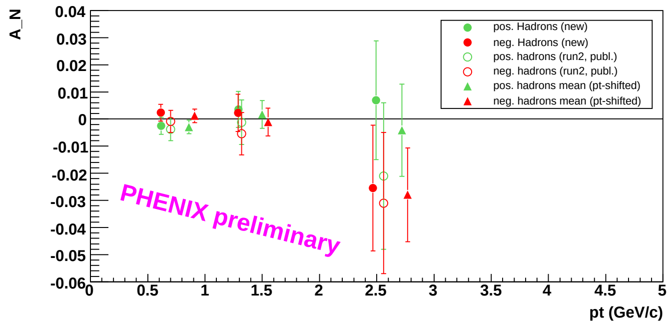

Fig. 3. Preliminary result from 2005 data on A_N for single charged hadrons at midrapidity. Previous PHENIX result is also shown for comparison. Additional scaling errors of 20% (present result) and 30% (previous result) due to uncertainty in beam polarization are not shown on the figure.

distribution function, $f_{1T}^{\perp}(x, p_T^2)$.[17] The Sivers distribution function is a correlation between the transverse-spin of the proton and the transverse-momentum of an unpolarized parton inside the proton (p_T^2), and it is related to the orbital angular motion of the quarks and gluons inside the proton. The other is a higher-twist effect which is also related to the orbital angular motion inside the proton, and recently combined with the Sivers effect in the QCD framework at a moderate transverse-momentum region.[18]

3.2 Results and Discussions

We have measured the A_N of neutral pion and charged hadron production in the mid-rapidity region. In the STAR measurement at the forward rapidity, the production mechanism is dominated by the quark-gluon scattering with a large contribution from $x \sim 0.6$ quarks, while in the PHENIX experiment at the midrapidity, the production is contributed by both gluon-gluon and quark-gluon scatterings with x of $0.03 - 0.1$. In this kinematic region, a contribution from the Collins effect is negligible, because there is no gluon transversity in the leading twist and the quark transversity is small. The measurement is sensitive to the Sivers effect of the gluon.

The results showed that asymmetries of neutral pion and charged hadron production at the midrapidity are more than 5-times smaller than the STAR forward rapidity data, and consistent with zero.[19] The results give a limitation to the Sivers distribution function.

Another result we have got in the transversely-polarized proton collisions is a A_N measurement of neutron production at the forward rapidity with the local polarimeter. A large asymmetry of forward neutron production was discovered in the IP12 measurement at RHIC for the development of the local polarimeter used in the PHENIX experiment.[6] We have measured large negative asymmetries by

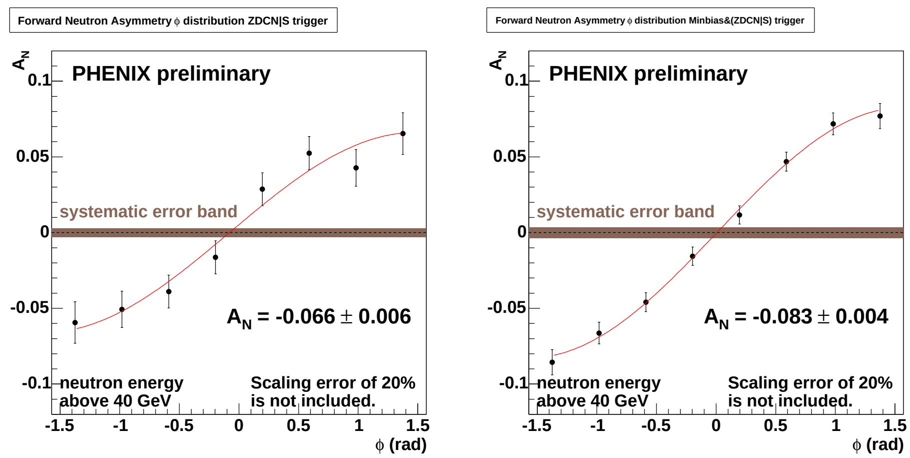

Fig. 4. A_N of very forward neutrons at $\sqrt{s} = 200$ GeV and $x_F > 0.4$. Left: A_N of single neutrons. Right: A_N of neutrons when other particles are detected in the region of $3.0 < |\eta| < 3.9$.

the local polarimeter consistent with the IP12 measurement with and without a minimum-bias trigger made by the BBC. In order to understand the production mechanism of this large asymmetry, we are measuring a production cross section of the forward neutrons. A_N is produced via interference of spin non-flip and spin-flip amplitudes. The one-pion exchange (OPE) is a fully spin-flip process, and may be able to explain the results. In ISR energies, the OPE model can explain the cross section, and show the x_F scaling at different energies. The cross section measured at PHENIX is also consistent with the x_F scaling.[20]

3.3 Outlook

In 2006, we had a radially transverse-spin run. The main interest in this run is a measurement of the back-to-back hadron-pair in the PHENIX central arm. Boer and Vogelsang find that the parton asymmetry will lead to an asymmetry in the $\delta\phi$ distribution of back-to-back jets. This asymmetry should also be seen with fragments of jets, and not just with fully reconstructed jets. Two arms of the PHENIX central arm located in the east side and west side of the interaction point can measure the $\delta\phi$ distribution of back-to-back hadron pairs to search for the Boer and Vogelsang's asymmetry. The asymmetry is caused by the Sivers effect of the gluon.

We will be able to use the MPC for the back-to-back hadron-pair measurement in the forward rapidity in the future.

4 Summary and Future Prospect

We have been accumulating and presenting data for both A_{LL} and A_N physics. We will accumulate $\sqrt{s} = 200$ GeV collision data until 2009, and will accumulate 500 GeV collision data from 2009. In A_{LL} measurements, our first goal is the ΔG measurement. The 2005 run data disfavored a large ΔG and excludes scenarios where $\Delta G = G$ (GRSV-max) and $\Delta G = -G$ are used at the input energy scale. In 2006, we took more data, A_{LL} data at $\sqrt{s} = 200$ GeV and 62.4 GeV of π^0, forward π^0, direct photon, and so on. Towards the future, we will measure flavor-identified quark polarization measurement with $W^{\pm}$ at $\sqrt{s} = 500$ GeV. In A_N measurements, we have shown results of π^0 and charged hadrons, and will show more results of back-to-back hadron-pair, neutron, and so on.

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